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An Interactive Gravitational-Wave Detector Model for Museums and Fairs

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In 2015 the first observation of gravitational waves marked a breakthrough in astrophysics, and in technological research and development. The discovery of a gravitational-wave signal from the collision of two black holes, a billion light-years away, received considerable interest from the media and public. We describe the development of a purpose-built exhibit explaining this new area of research to a general audience. The core element of the exhibit is a working Michelson interferometer: a scaled-down version of the key technology used in gravitational-wave detectors. The Michelson interferometer is integrated into a hands-on exhibit, which allows for user interaction and simulated gravitational-wave observations. An interactive display provides a self-guided explanation of gravitational-wave related topics through video, animation, images and text. We detail the hardware and software used to create the exhibit, and discuss two installation variants: an independent learning experience in a museum setting (the Thinktank Birmingham Science Museum), and a science-festival with the presence of expert guides (the 2017 Royal Society Summer Science Exhibition). We assess audience reception in these two settings, describe the improvements we have made given this information, and discuss future public-engagement projects resulting from this work. The exhibit is found to be effective in communicating the new and unfamiliar field of gravitational-wave research to general audiences. An accompanying website provides parts lists and information for others to build their own version of this exhibit.

I. INTRODUCTION AND OVERVIEW

Gravitational waves are ripples in space and time first predicted as a consequence of the general theory of relativity by physicist Albert Einstein in 1916[1]. A century later and after decades of technological development, the first observation of gravitational waves was on the 14 September 2015[2]. The signal came from two black holes orbiting each other a billion light-years from Earth[3,4]. The black holes merged together, creating a new bigger black hole. The gravitational waves produced by this event spread out across the Universe, eventually reaching the Earth, where their miniscule effect was detected by the Laser Interferometer Gravitational-Wave Observatory (LIGO)[5]. LIGO has since been joined in observing gravitational waves by Virgo[6] and future detectors are planned with KAGRA[7] and LIGO India[8]. The current global gravitational-wave detector network has made many new observations[4,9–15]; the beginning of a new kind of astronomy.

In anticipation of increased media coverage and public interest in gravitational-wave astronomy brought about by the first detections, the Education and Public Outreach (EPO) group of the LIGO Scientific Collaboration has worked to develop resources and activities aimed at informing and inspiring the general public, prospective students, and the wider scientific community about our work[16,17]. Our group at the University of Birmingham has a strong history of involvement with public engagement with research[18,19]. Here, we describe our work developing an interactive model gravitational-wave detector designed to demonstrate the key technologies that have enabled gravitational-wave astronomy, and introduce the public to this new field of astronomy.

Museum and science-fair exhibits are an effective way of increasing interest in science[20–22] and raising awareness of scientific concepts[23–25]. Visits to science museums have been shown to improve long-term science knowledge[26] and adult memories of school field trips can often recall something learnt during their childhood experience[27]. We have created an interactive exhibit that can be used both when an expert is present to explain it and as a stand-alone,non-facilitated piece which a member of the public can use to learn independently. The exhibit teaches the public about gravitational waves, how they have been detected, and the kinds of astrophysical events which can be observed using them. The resulting piece is a long-term installation at the Thinktank Birmingham Science Museum (Thinktank) and was featured at the 2017 Royal Society Summer Science Exhibition (RSSE).

In this article we provide a detailed description of the design and implementation of our exhibit. We provide an overview of the distinguishing features of our exhibit in Section II, and cover the technicalities of the hardware and software in Section III, with links to the detailed design for others to use[28]. In Section IV and Section V we describe two use cases of the exhibit in a museum and science fair setting respectively. Finally in Section VI, we discuss the impact of our exhibit, measured through surveys as well as anecdotal examples of the public reception, and look to the future of these activities in Section VII.

II. DESIGN CONSIDERATIONS

Gravitational-wave science involves wide extremes of scale in the Universe. The colliding black holes and neutron stars that we observe have masses many times the mass of the Sun and can be billions of light-years from Earth. However, the resulting gravitational waves arriving at Earth create minuscule changes in distance: a typical black hole collision moves the components of the LIGO instruments by a thousandth of the width of a proton. To detect such changes, high-precision instrumentation is required, and on a large scale: each detector site is several square kilometres. It can therefore be challenging to communicate the science of gravitational waves in a human-relatable way.

Our exhibit is a model gravitational-wave detector, demonstrating the core technology of current detectors like LIGO: the *Michelson interferometer*[29]. This optical configuration is often used to measure changes in distance; this is explained further in Section III. The exhibit highlights both the behaviour of gravitational waves—changing relative distances on a small scale—and the technologies necessary to measure this behaviour. Such an interferometer is a common item in the tool-kit of gravitational-wave education and outreach and is often used in undergraduate laboratory experiments[30–33]. The University of Birmingham has expertise in designing and building instruments such as interferometers. Therefore, it was possible for us to build our own exhibit, and in doing so showcase both the technical expertise and research of the University in this field.

The exhibit design is driven by three main aims: (a) present gravitational-wave topics and concepts so that they are accessible for a broad audience, (b) attract interest in the exhibit using an appealing and exciting design[34,35], and (c) be suitable for use in both a museum and a science-fair setting. In a museum, an exhibit needs to work as a stand-alone piece, whilst at fairs it is accompanied by experts to guide a visitor through the demonstration and answer any questions. Exhibiting at the Thinktank allows us to engage our local community, highlighting the activities taking place in the city of Birmingham. The RSSE was a national science fair providing us an opportunity to work in collaboration with several other universities.

The audiences in both settings are typically non-scientists with a general interest in science. We engage our audience by pitching the exhibit material to the right level, enabling them to build upon their current understanding[24,36,37], and conveying the subject in an interactive[38–40], varied and fun way[41,42].

Our initial design considerations were the size and weight of the model, how the public would interact with the exhibit in its stand-alone use case within the museum, and how demonstrators would interact with the exhibit when explaining gravitational-wave science to small groups at fairs[43]. We wanted the gravitational-wave detector model to be as large as feasibly possible: aesthetically we wanted something shiny and interesting to the public[35], and practically the larger size allows the components to be more easily viewed. At the same time, the model needed to be small enough to be easily transported for events and to and from the museum. We settled on a circular aluminium base with a diameter of 0.6 m, which can be easily lifted by two people and fits into a compact car. The circular shape also allows for people to easily gather around the model at fairs[41,43].

The gravitational-wave detector model can be used on its own, or in combination with screens and buttons that visitors can use to interact with the model and learn more about it[42,44]. We have developed custom exhibit software, which can be adapted to suit a specific audience and the particular interactive configuration in use, either in a museum or at a science fair (see Section IV and Section V for details on these audiences).

In the museum, the software is set up so that users can guide themselves through the exhibit with the help of multimedia material. The software and interaction with the physical hardware needed to be durable to cope with high usage and to operate independently without maintenance for extended periods of time. It also needed to follow the museum's health and safety protocols to be suitable for unsupervised use by all ages. The information presented needed to be self-explanatory, suitable for a range of interaction times, and use a range of information delivery options (e.g., video, images, text).

At the Thinktank, our exhibit is located in a gallery containing several unrelated science exhibits. Each is housed in a large bay (approximately 2 m × 3 m) fronted by a low barrier, with a main prop placed in the centre, approximately 1.5 m from the viewer. Our gravitational-wave detector model therefore needed to work with the museum's existing infrastructure.

The nature of a science fair requires a short setup time: assembly needed to be simple and efficient. The interferometer needed to be safe for the public (especially curious children), and produce responses that aid the demonstrators' explanation, such as live data feeds. At the RSSE our model formed part of a collection of gravitational-wave related demonstrations, which were continuously staffed by a team of 10 demonstrators who act as guides to visitors. Due to the broad range of expertise of the team, a technical manual was necessary to train people to operate the interferometer and software. In both settings we use a high aesthetic appeal and technological novelty to attract visitor attention[35,42,45].

III. TECHNICAL DESIGN

A. Hardware

Gravitational-wave detection requires measurement of small changes in distances. A gravitational-wave detector can be thought of as a precise ruler. The key component of gravitational-wave detectors like LIGO and Virgo which enables this precise measurements is the *Michelson interferometer*[29]. The model gravitational-wave detector is a working Michelson interferometer. It compares the paths of two laser light beams to detect changes in distance. While it cannot detect gravitational waves, it can pick up vibrations in the room, even when there is no apparent disturbances to the exhibit. This provides an intuitive means to illustrate that these instruments are capable of sensing vibrations imperceptible to humans.

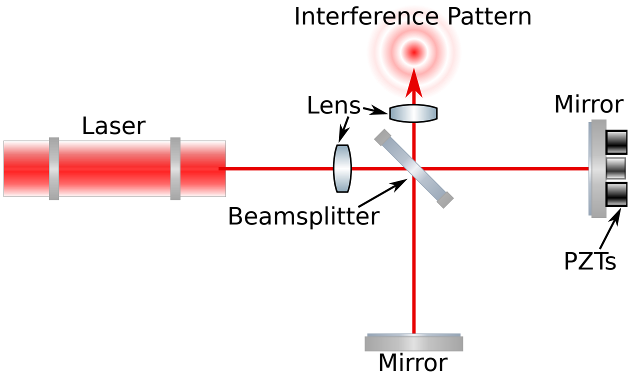


FIG. 1. Schematic optical layout of a Michelson Interferometer. A beamsplitter is used to split laser light equally into two perpendicular directions. Each beam reflects off a mirror, and the two beams recombine again at the beamsplitter. The interference pattern appearing at the output of the interferometer depends on differences between the two paths taken by the two beams. Piezoelectric transducers (PZTs) are used to precisely move one of the mirrors, changing the interference pattern to simulate an observation of the gravitational wave.

The core constituents of a Michelson interferometer are a laser, two mirrors and a beamsplitter as illustrated in Fig. 1. The laser beam first hits the beamsplitter, where it is split in two. The beams travel in two arms at 90° to each other to mirrors at the ends of each arm. After reflecting from the mirrors, the light from the two arms recombines at the beamsplitter where the two beams interfere. The resulting light hits a screen where it can be viewed

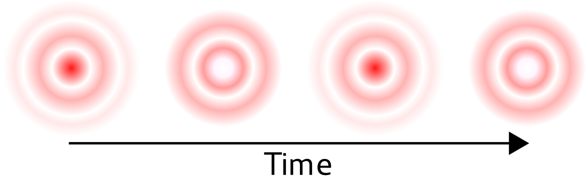


FIG. 2. Illustration of the ring interference pattern produced by our interferometer. When the interferometer is disturbed, the resulting concentric rings of the interference pattern change over time (left to right in the illustration) from light to dark and back again.

and it is this recombined light that produces the changing *interference pattern* produced by the interferometer, i.e. the output of the detector changes from dark to light when a gravitational wave passes through the detector.

The interference pattern in LIGO is a single spot of light changing over time. To demonstrate the changes clearly to our audience, we used lenses to create an extended interference pattern of a series of concentric rings as illustrated in Fig. 2. When there is no change in distance, these rings remain still, but if there is some disturbance to the interferometer the rings will either breath in and out (for small motions) or seem to be zooming in or out (for larger motions). By viewing the interference pattern, the audience can build an understanding that zooming in one direction or the other corresponds to the detector sensing either an increase or decrease in distance. Fig. 2 gives an examples of how the rings' motion makes both the direction and the magnitude of the motion visually apparent, while maintaining a LIGO-like operation.

This basic setup of the interferometer can be built with all grades of components, from inexpensive craft mirrors and laser pointers suitable for classes of students to lab-grade optics. The majority of the optical components we use (beamsplitter, mirrors, mounts, etc.) are either lab-grade parts, or bespoke parts manufactured by the University of Birmingham's mechanical workshop (see the accompanying website[28] for example parts). This ensures the long-term stability of the configuration, achieves a shiny aesthetic appeal, and allows the public to encounter equipment which is frequently used in research laboratories. Large mirrors and a large beamsplitter (all 2-inch diameter) are used to increase their visibility and emphasise their importance. The resulting exhibit Michelson is shown in Fig. 3 with the laser on the left. The exhibit contains more components than shown in the Fig. 1 schematic: in addition we use a screen and a webcam to display the interference pattern and record it.

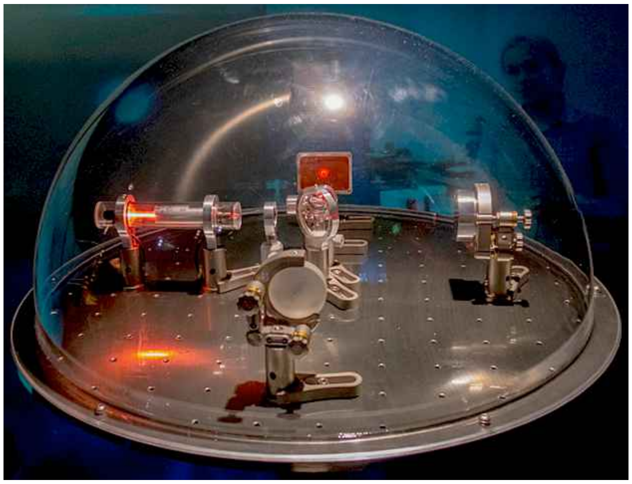


FIG. 3. The Michelson interferometer at the core of our exhibit, shown in situ at the Thinktank Birmingham Science Museum.

We use a helium–neon (He–Ne) laser with an exposed view of the glowing gas. Seeing the glow of the exposed laser both attracts audiences and emphasises the light source of the setup. We use a class 1 laser for safety reasons and ensure that all beams are contained in the circular base plate. The primary hazard is the high voltage required for the laser (1 kV when running). All active components are encased in a plastic box underneath the optical base so that these cannot be accessed. The laser is mounted inside an acrylic tube with acrylic end-caps, and grounded to the base plate. The laser and all optics are encased inside an acrylic dome, protecting the optical components from damage and misalignment.

This risk of laser induced eye damage is extremely remote due to the use of a low-powered laser and inability to misalign the interferometer. The Computer Aided Design (CAD) for the full bespoke laser mounting is shown in Fig. 4.

LIGO is fine-tuned and controlled so that the interference pattern is almost completely dark unless a gravitational wave passes through the detector. Our interferometer reacts to any kind of shaking motion, meaning that the interference pattern constantly flickers. To observe the interference pattern we tested a large variety of screen materials. The brightest, highest contrast pattern was observed using red card. The use of two diverging lenses (focal

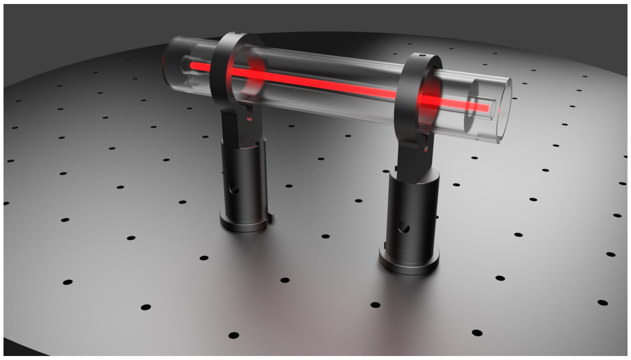


FIG. 4. Computer aided design used to develop bespoke parts for the exhibit. The exposed He–Ne laser tube was housed inside an insulating acrylic tube and mounted on adapted lab-grade posts. This image was rendered using Blender[46].

length −50 mm) allows us to create a large beam-spot. These, combined with a small difference in the interferometer's arm lengths, produce the ringed interference pattern that changes depending on the relative length of the arms.

The Michelson interferometer described here can be used as a stand-alone piece. In this configuration, it is well suited for use with small groups under the guidance of a trained demonstrator, enabling more direct engagement[40,47]. For example, the outer dome can be removed and properties of the interferometer explored, such as demonstrating alignment of optics, or pushing on the base to bend it slightly, changing the relative arm lengths.

Without a trained demonstrator present, it is difficult for the public to interact with the interferometer in a meaningful and safe way due to the requirements of safety and robustness. To solve this problem, custom exhibit software was developed to allow the user to learn more about the exhibit (Section IV), and interact directly with the interferometer without the need to physically touch it. This reduces the risk of damage to the equipment or misalignment of the interferometer, and ensures that the interactions with the exhibit are meaningful and repeatable. This interaction mechanism uses three piezoelectric transducers (PZTs) mounted behind one of the end mirrors in an equilateral triangle to minimise the tilt of the mirror. The PZTs convert electrical voltage into motion, moving the mirror by up to 2 µm. They are driven using a combination of a Raspberry Pi and an Arduino Uno. Through the PZTs, the user can *send a gravitational-wave signal*, a set of predefined custom signals, to the gravitational-wave detector model. These simulated signals are amplified and simplified versions of the kinds of waveforms that LIGO and Virgo are searching for. There are two chirp signals similar to those observed so far from merging black holes and neutron stars[4], and two as yet unseen signals: a continuous-wave signal which is expected from rotating neutron stars[48], and a burst signal which could come from events like supernova explosions[49]. The simulated signals, while not exact replicas of the real events, produce visually different interference patterns, allowing members of the public to see the connection between an astrophysical object and the interference pattern observed in a LIGO-like detector.

The user can push one of four buttons to select a gravitational-wave signal. We use four arcade-style buttons chosen for their colourful and rugged nature; the bold design makes them easy to identify, attractive to children and suitable for prolonged use[50–53]. The chosen gravitational-wave signal is sent to the Raspberry Pi and then to the Arduino Uno, which transfers the signal to the PZTs, resulting in a moving interference pattern. Although the actual motion of the mirror is undetectable by eye (a few hundred nanometres), the change in the interference pattern is apparent, giving an indication of the precision measurements possible with real gravitational-wave detectors. The average maximum frequency for each of the detections during the first and second observing runs of LIGO and Virgo is several hundred hertz[2], whereas the human eye struggles to notice flickering over 25 Hz. The signals are therefore designed to fit this frequency limit and are amplified by twelve orders of magnitude when compared with the real signals to make their effect clear.

The ability to interact with the exhibit stimulates members of the public to ask more in-depth questions on the nature of the exhibit and also the of the real gravitational-wave detectors[39,47]. At science fairs, jumping or walking near the exhibit provoked questions about how to remove seismic noise from the detector output. This creates an opportunity for demonstrators to talk about different noise sources in the detector. As the output signal is not perfect, it also encourages questions about the data analysis involved to identify and characterise astrophysical sources.

B. Software

Museum exhibits need to be self-explanatory[43]: typically a specialist will not be present to guide the user or answer any questions. To achieve a self-explanatory exhibit, we use interactive software to present a mixture of video, images, and text, providing a varied range of learning materials[54]. The specific configuration of software and hardware used in the Thinktank and the RSSE are detailed in Section IV and Section V, respectively.

There is existing software to create museum exhibits, such as Open Exhibits[55] or Intuiface[56]. A drawback of these is that they are either written in older programming languages such as Actionscript 3, as is the case with Open Exhibits, or are costly to design and run, like Intuiface. Existing solutions therefore lacked the flexibility required for our exhibit.

We have developed our own exhibit software based on a number of Javascript libraries including reveal.js, socket.io and johnny-five[57–59]. The advantages of using these libraries are that they; are modern; have a relatively low barrier to entry; can be visualised easily through the use of HTML and CSS, which are key web technologies; are easy to develop; and are widely supported and will be supported for years to come. This allowed more time and effort to be spent on content creation, rather than the functionality of the exhibit. Wide support for this software makes installation in a variety of locations, with different sets of requirements, easier to manage. The packages used in this project are also open-source, reducing the overall cost.

The software is flexible in terms of the available features and customisation. It can be used with one or two display screens and is touch-screen compatible. A set of navigable pages can be created in order to guide a user through the materials. The top-level menu provides a selection of topics, leading to sub-pages with further information. This allows users to direct their own learning[42,52], and potentially build upon the understanding achieved at a previous visit[25]. Within the sub-pages, a combination of animations, images and text can be displayed. The display can also be timed to return to the home screen after a set idle time, which is desirable when the exhibit software has been left on a sub-page so that it is ready for the next user. Selecting a topic can also trigger a pre-recorded video to begin playing, as well as simultaneously displaying live data from the exhibit.

In the gravitational-wave detector model, a webcam is used to show an enlarged view of the current interference pattern on the screen, and a photodiode embedded in the centre of the screen takes a light intensity reading, which is live-plotted using custom-written graphing software. This helps larger groups of people to clearly see the interference pattern from a distance and the changing intensity reading in response to different signals. A schematic view of all the signal paths used in our exhibit is shown in Fig. 5. As described in Section III A, the user can directly interact with the exhibit via a selection of buttons. Pressing one of these selects a simulated gravitational-wave signal to send to the interferometer. The buttons can also be lit up in patterns via the software, making them attractive to push.

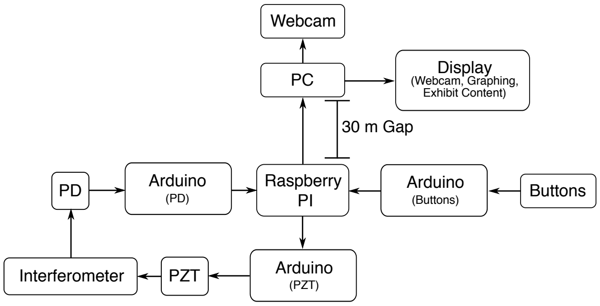


FIG. 5. Signal flow chart for the exhibit. A Raspberry PI runs the exhibit software and interfaces with the piezoelectric transducers (PZTs) and the photodiode (PD). When used at the Thinktank Birmingham Science Museum, the PC is separated by 30 m from the rest of the exhibit, so communication must be be done via ethernet rather than a simpler, faster USB connection (USB is limited to 5 m).

IV. LONG-TERM INSTALLATION AT THE THINKTANK BIRMINGHAM SCIENCE MUSEUM

The Thinktank is part of Birmingham Museums Trust[60], a registered charity responsible for management of museum sites and collections owned by Birmingham City Council. There are eight museum sites managed by Birmingham Museums Trust, including the Birmingham Museum and Art Gallery and Sarehole Mill as well as the Thinktank Birmingham Science Museum[61]. The Thinktank receives 230, 000 visitors per year, including 45, 000 from schools, 10, 000 from other school-aged groups, and 152, 000 general visitors, 95% of whom visit with children[62]. It houses a wide variety of objects and exhibits, ranging from natural sciences, including fossils and wildlife specimens, to science and industry, including a planetarium and a large collection of steam engines.

One of our main considerations when translating our experience with hands-on demonstrations to a longstanding museum piece was developing a robust design. Accessibility of information is also important. It is impractical for a museum exhibit to require an expert person present to explain it at all times; therefore, we needed to find alternative ways to convey our enthusiasm for the subject.

The exhibit, initially installed in June 2016[63,64], is housed in the Futures Gallery. The gallery consists of a series of bays, each focused around a central prop, as depicted for our exhibit in Fig. 6. Props are mounted to a narrow post connected to a raised false floor which curves up to form a low (approximately 0.4 m high) barrier between the prop and the public, and allows cabling to be fed to any part of the exhibit. A large back-projected screen at the rear and smaller, interactive computer screen attached to the front barrier provide additional multimedia content. Sound is played to visitors via an overhead directional speaker. Finally, a static text panel provides an overview of each exhibit, and ensures that some information is still available in the event of a technical fault.

This configuration means that visitors to the gallery have no physical contact with the prop on display: all the interaction is made through the computer screen and buttons at the front of the exhibit. However, the low barrier means that it is easy for the visitors, for example young children, to climb over and touch props. As such, we made sure that the post attachment of our interferometer to the false floor was sturdy, and included an acrylic dome to both protect the public from the high voltage laser, and protect the Michelson optics from stray fingerprints, dust, and getting knocked out of alignment.

The exhibit was built to ensure its long-term stability. This included, for example, ensuring that the optics do not move significantly over time or with temperature; choosing software packages that will not become rapidly deprecated and can be easily upgraded; and designing electronics and computers to survive the power cycling in the Futures Gallery at the end of each day. This stability means that we can provide occasional on-call support, rather than requiring local staff to be trained.

The Michelson interferometer itself was positioned to be ergonomically suited to the core audience of the Thinktank[65,66]. It is 1.2 m high, tilted 25° forward, and located in front of the rear projected screen, which is predominantly used to display video content.

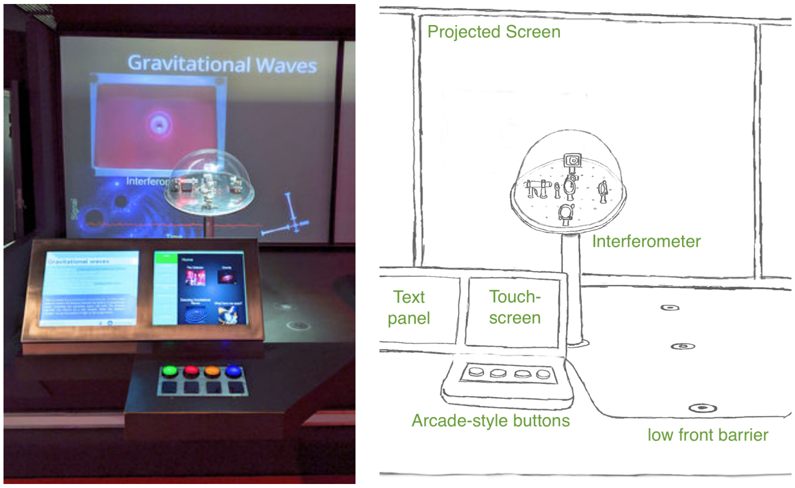
The rear projected screen constantly shows a large live feed of the interference pattern, allowing visitors to clearly see a zoomed in view of how the pattern changes due to floor vibrations as they move around, or as they simulate a signal via the arcade buttons. A simultaneous view of the actual pattern on the screen inside the interferometer dome, along with real time graphing of the photodiode output, shows that this video is indeed a live feed from the instrument they see in front of them

In a museum setting, visitors will often spend limited time interacting with any particular exhibit. It is important to make the scientific information quick and easy to access, whilst also providing depth and variety for longer interactions[43]. The software described in Section III B was developed specifically to achieve this, and to enable direct interaction with the exhibit. The content was developed in collaboration with the Thinktank to ensure the language was suitable and accessible for both children and adults. The colour scheme was checked to be colour-blind friendly using Color Oracle[67] and the fonts chosen were sans-serif as there are indications that these fonts may be more dyslexia-friendly[68,69].

There are two points of user interaction in the museum installation of the exhibit. First, the touch-screen computer in front of the exhibit, and secondly the four buttons used to simulate exaggerated examples of gravitational-wave signals. The buttons can be pressed at any time during interaction with the exhibit. The touch-screen provides a selection of topics and a quiz.

Typically, selecting a topic will trigger a short (under 90 s) video to play on the rear screen, during which visitors are free to click through several short ($<$ 80 words per page) text[25,52] and graphic pages that expand on the content of the video. The video duration is displayed on the screen, so that a viewer is aware that the video is short[70]. An example of the touch-panel display is shown in Fig 7. Gravitational-wave astronomy is an area of current rapid progress; therefore, the software has been configured to allow for periodic expansions as new research results emerge, and to provide new content for the repeat visitor[43].

The videos themselves cover four core topics: (a) an explanation of the gravitational-wave detector model on display and what the interference pattern means; (b) the nature of gravity and how gravitational waves are produced; (c) how interferometers are used to search for gravitational waves; (d) the detection of gravitational waves, including the first detection in 2015 and other observations since. Each video is subtitled, and features enthusiastic members of our group as well as video clips, graphics and animations created by others in the LIGO Scientific



(a) Photograph (b) Sketch

FIG. 6. Our exhibit as configured for use in the Thinktank Futures Gallery. Visitors stand next to a touchscreen panel which they can use to select from a range of topics and either read, watch videos, or take a quiz. Pushing the arcade-style buttons sends a signal to the driven mirror, emulating the effect of different types of gravitational wave signals. The interferometer model itself is mounted at an angle on a narrow post behind a low barrier approximately 1 m from the viewer. All cables to and from the model, touch-screen, and buttons are concealed inside the post and under the raised false floor. Approximately 2 m from the viewer, at the back of the exhibit, a second projected screen displays a live feed of the interference pattern alongside the currently selected video. The static text panel to the left contains some overview information about the exhibit.

Collaboration[71]. This is intended to help the public make a human connection to the science we discuss, and to share in our excitement for the subject[43,45]. The four presenters (two female and two male) were all PhD students from the University of Birmingham Institute for Gravitational Wave Astronomy. Student presenters were chosen as we considered them to be more relatable and intentionally avoided the old-professor stereotype of a physicist[25,39,41]. The videos were produced in collaboration with the communications department of the College of Engineering and Physical Sciences at the University of Birmingham.

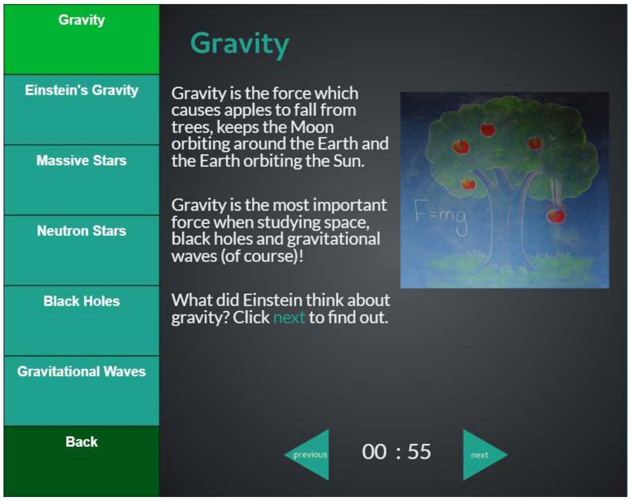
Finally, the quiz option facilitates a more active interaction where the user can test their knowledge and receive confirmation of their understanding[72]. The quiz is intentionally short (four questions) and displays the final score in a chalk-board image next to Einstein.

In summary, the software, interferometer and static display together provide the capability for varying levels of self-guided interaction within a museum setting. A short engagement allows for a little information about gravitational waves to be gained; however, much more detailed information is available if a visitor chooses a prolonged interaction.

V. THE ROYAL SOCIETY SUMMER EXHIBITION

The RSSE[73] is an annual week-long festival hosted at The Royal Society in London, celebrating cutting-edge science and technology in the UK. Each year, around 20 teams from university research groups and industry are selected to develop a science-fair style exhibit, staffed full-time by members of each group. The week caters to a range of audiences, including days for school groups, a Twilight Science open evening, press and media sessions, evening soirées for selected guests including politicians and celebrities, and is also open to the general public. The layout of the RSSE is such that visitors move from one exhibit stand to the next.

In 2017, UK members of the LIGO EPO group[74] were selected to jointly host a stand at the RSSE named *Listening to Einstein's Universe*[75,76]. The space for our stand was a 4 m × 2 m area, partially surrounded by printed fabric panels, creating zoned areas that visitors could walk through to interact with several activities and props representing different areas of our research. Our group from the University of Birmingham provided two key components of the stand: (a) a series of apps and games, which



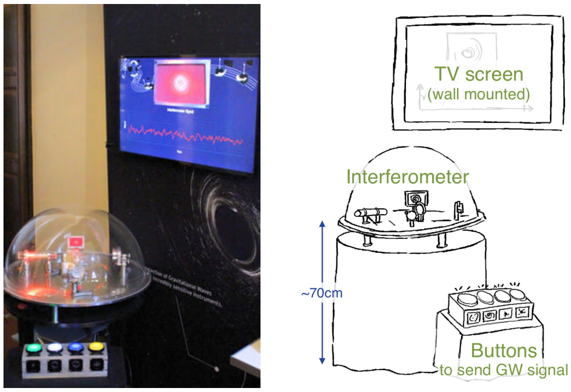
Gravity

Gravity is the force which causes apples to fall from trees, keeps the Moon orbiting around the Earth and the Earth orbiting the Sun.

Gravity is the most important force when studying space, black holes and gravitational waves (of course)!

What did Einstein think about gravity? Click next to find out.

FIG. 7. A screenshot of the custom exhibit software as used in the Thinktank. The screenshot shows one of the topic pages—from the main menu users select a topic they are interested in (gravity in the case shown here). They can then navigate through these information pages using the menu shown on the left-hand side, or by using the *previous* and *next* buttons at the bottom. They can then return to the main menu via the *Back* button in the bottom-left. The timer in the bottom-center indicates the duration of any videos currently playing in seconds.



(a) Photograph (b) Sketch

FIG. 8. Our exhibit as configured for use at the RSSE 2017. The gravitational-wave detector model is mounted on three feet and sits on a round table 0.7 m above the floor. Additional electronics and resources as concealed on a lower shelf behind a table cloth. The arcade-style buttons are housed in a separate box on an independent low table, so that pushing a button does not shake the interferometer. A 40-inch television screen is mounted into the fabric panelling of the *Listening to Einstein's Universe* stand (on the upper-right), and displays live feeds of both the interference pattern, and a graph of the resulting measured signal.

have been developed by the Birmingham group over the last 10 years[18,77,78], and (b) our gravitational-wave detector model, on loan from the Thinktank.

The hardware and software configuration used at the RSSE is depicted in Fig. 8. In comparison to that used in the Thinktank (see Section IV and Fig. 6), the core components—the interferometer and a display screen—were identical; however, the interactive self-guided content was not required because experts would always be on hand to explain the model in person. Instead, a smaller single television screen was used to show the live video feed of the interference pattern alongside a graph plotting the intensity of light at the centre of the interference pattern over time. The simplified display allowed for tailored explanations to suit each visitor: a short overview at times of high footfall (such as for school groups), or an expanded explanation when time and visitor interest allowed. The additional electronics required for the RSSE setup were concealed on a lower shelf behind a tablecloth. The arcade buttons were housed in a separate box to prevent the physical button press shaking the exhibit and drowning out the injected signal. The graph plotter and button box were first developed for the RSSE and subsequently implemented at the Thinktank.

Over the course of the week, approximately 30 volunteers staffed our stand in rotation, with varying levels of expertise in interferometry, hardware, and software engineering. We produced a manual for general maintenance of the model, and one of the Birmingham team was available if any further questions arose. The robustness and safety of the design required for the Thinktank meant that transporting the model was relatively simple, and that the installation time and maintenance of the exhibit were minimal.

The model was located towards the back of the *Listening to Einstein's Universe* stand; therefore, the aesthetic choices made to attract visitors at the Thinktank, such as the use of bright coloured lights and shiny components, were advantageous here too[43]. The dome on the interferometer meant that we could safely invite visitors to take an up-close look at the optics, which was not only useful for explaining the model but also a necessity in the compact space.

The combination of aesthetic and practical design choices made for a museum setting also resulted in a model that is robust and exciting to use at science fairs such as the 2017 RSSE. By adapting the multimedia content provided, the configuration of our exhibit can be tailored to suit a wide range of contexts.

VI. IMPACT

Our exhibit was installed at the Thinktank in June 2016. Since then, it has spent over two years housed at the Thinktank Birmingham Science Museum, as well as being included as part of the *Listening to Eintein's Universe* stand at RSSE. An early prototype was featured on the UK's Channel 4 news during the media campaigns surrounding the announcements of the first gravitational wave and first binary neutron star detections. Each stage of the exhibit's life has enabled us to explore different aspects of user engagement and reception, as well as the broader impact of the project. In this section, we describe our feedback collection at the RSSE and the improvements we have implemented to the exhibit based on experiences gained in a science-fair setting. We also describe how observations in the museum setting led to further modifications. Finally, we consider the wider impact of the project for our group and the collaborations and opportunities resulting from it.

A. Feedback from the Royal Society Summer Science Exhibition 2017

As described in Section V, the RSSE is an annual, week-long festival celebrating innovation and advancements in science, technology, engineering and mathematics (STEM) research by British research groups and companies. It is open to all and free. The audience ranges from school groups and the general public to politicians and celebrities.

In 2017, 10,123 members of the public, 2002 students and 262 teachers visited the RSSE[79]. School groups (age 14+) are required to register in advance to attend the dedicated sessions, bringing up to 25 students per group[80]. This means that students at the RSSE are more likely to be from schools with proactive class teachers who were motivated to pursue out-of-classroom activities, and the students themselves are a sub-selection from their year group or class (e.g., most interested, most likely to benefit from attending, etc.), biasing the sample compared to the entire population of schoolchildren. The audience at the RSSE is therefore not ideal for engaging hard-to-reach demographics with research.

Survey respondents	**Total (Paper | Electronic)**
Total responses	171 (63 | 102)
Identifying as:	
female	39% (34% | 40%)
male	55% (52% | 58%)
other/not specified	6% (14% | 2%)
Aged 18 or under	51% (84% | 31%)

TABLE I. Demographic overview of survey respondents at the RSSE 2017. The labels Paper and Electronic signify whether the information was gathered via paper form (used mostly for younger people) or the electronic form via tablet.

The Exhibition was an opportunity to showcase the LIGO Scientific Collaboration's work to both the public and to high-profile individuals. The high foot-fall and many in-person interactions provided an occasion to gather feedback and measure the impact of our exhibit.

We created two types of survey that were used throughout the week. The first used an established electronic survey platform, completed via a pair of tablets at the exhibit stand. This targeted individuals or small groups, typically older teenagers or adults. Questions typically asked the user to rate their opinion on a Likert scale from 1 to 5. The second survey format was on paper, aimed at younger attendees by using a range of graphical question formats rather than the traditional multiple choice questionnaire. This format was also better suited to large groups since the paper forms could be distributed quickly to an entire class. The surveys were created to be short, with eight and ten questions for the paper and electronic versions respectively. Both versions took no more than a few minutes to complete.

The questions within each of the two survey types were not identical (due to the different survey formats); however, both aimed to assess change in the individual's interest in physics and gravitational-wave research, as well as their interest in specific parts of the *Listening to Eintein's Universe* stand. The demographics of those surveyed through both formats are summarised in Table I. A conscious effort was made to maintain a gender balance across each session of those surveyed over the course of the week.

A summary of responses to key survey questions is given in Table II. While the surveys generally discussed the exhibit as a whole, many people spent a significant fraction of their time at the interferome-

How much has your knowledge of gravitational waves changed?	*No change*	*Large increase*
(Electronic)	1%	80%
How much has your knowledge of LIGO changed?	*No change*	*Large increase*
(Electronic)	7%	66%
Rate your interest in physics before & after visiting the RSSE*	1-step increase	2-step increase**
(Paper)	49%	13%

TABLE II. Selected survey results from the RSSE 2017. The left column shows the question where the labels Electronic and Paper are as described in Table I. The right columns show some key results.
* 83% of those specifying no change were already *Highly* or *Very highly* interested in physics before attending the RSSE. Most people described their interest before the RSSE as *OK* (32%) or *High* (32%), and after the RSSE as *Very highly* (51%). Percentage increase in interest across genders: female 75%, male 48%, other/undisclosed 75%.
** All of those specifying a 2-step increase were aged 11–16 (22% of 14–16 year-olds and 8% of 11–13 year-olds)

ter model, and, therefore, the results are considered reflective of the model gravitational-wave detector.

According to questions from the electronic survey, we found that *Listening to Eintein's Universe* was successful in both its core goal of increasing people's awareness of gravitational waves (80% *Large increase*), and in informing them about LIGO (66% *Large increase*), which was just one of several research projects mentioned at the exhibit. Similarly, the paper survey indicated that 62% of those asked were more interested in physics than they were previously, while a large majority of the rest were already *Highly interested* in physics before they arrived. Further analysis was possible using the data from the paper forms. The exhibit was particularly effective at engaging some of the 11–16 age range: all of those indicating a large increase in interest in physics (8 of the 63 people surveyed) were in this age bracket. It also effectively engaged girls, 75% of whom indicated increased interest. It is possible that this is a result of our efforts to deliberately include both male and female volunteers in every session of the exhibition.

These results indicate that we had a positive impact on those who attended, but cannot tell us more, such as long-term impact on the attendees, how we might improve our engagement with the public using the interferometer in the future, or how to reach audiences who have less prior interest in, or access to, STEM subjects. This is an area of active exploration for the group in the future.

B. Feedback from the Thinktank Futures Gallery Installation

We now consider our exhibit installation in the Thinktank, with a focus on the audience reached and the changes we made over the course of the installation. With a long-term installation, the exhibit can come into contact with more people over a prolonged duration.

In order to gauge the impact of our exhibit in this setting, we monitored visitor interactions with the exhibit and performed a short survey in the museum. The number of survey participants was small, and thus robust conclusions could not be drawn based on response statistics. Despite the small participation, we found some useful information and several areas of improvement were clear from observations of museum visitor behaviour and interaction.

In its first iteration, the exhibit was placed towards the back of the Futures Gallery in a relatively dark corner. Opposite this position was one of the museum highlights: *RoboThespian*, a talking, singing robot. Many visitors were observed to head directly for the robot, skipping the back corner of the gallery entirely[43]. On the day of the survey, only 13 of 200 people who entered the gallery interacted with our exhibit. In light of this behaviour, we have worked with the museum to place our exhibit closer to the gallery entrance, providing both a more prominent position, where visitors are liable to spend more time[43], and also offering better lighting to attract the visitor.

Of 13 people who interacted with the exhibit, nine took part in the survey. They were asked about their prior knowledge of gravitational waves. We found that three had not heard of gravitational waves before seeing the exhibit and none had any awareness of the University of Birmingham's involvement in the discovery of gravitational waves. All found the exhibit at least *Quite informative* and *Fairly easy to use*.

Our observations at the Thinktank, and our experiences at the RSSE, led us to make modifications to improve upon the museum installation design. The initial installation did not have interaction buttons, or a navigable touch screen. The only means of interaction with the exhibit was through a roller-ball mouse and a single click button. In the RSSE, we found that the interaction worked well through the arcade-style buttons. The subsequent addition of a touch screen has brought the exhibit more up-to-date with modern technology and, therefore, more familiar to the visitor[44].

Our future work will included continued monitoring of visitor interaction with the exhibit to assess the success of the modifications and new position, as well as further areas of improvement.

C. Wider Impact

We also consider the wider impact of this work. The experience gained in designing, implementing and evaluating the exhibit, as well as exposure to science communication professionals, has enabled us to explore new means of sharing gravitational-wave science to non-expert audiences in engaging and accessible ways. It has also led to further work beyond the exhibit itself.

One such project is an interdisciplinary collaboration with audio–visual digital artist Leon Trimble[81]. The project, *Gravity Synth*, is a musical instrument combining a Michelson interferometer with a modular synthesiser[82]. The interference pattern from this interferometer is converted into sound via a photodiode, and processed through a modular synthesiser, exploring the relationship between gravitational waves, vibrations and sound. The Gravity Synth has been performed at a variety of events ranging from arts and music festivals such as Lunar Festival (2018), Future Everything (2018) and The Superposition (2017), to science orientated events including Cheltenham Science Festival (2019), Pint of Science (2017), Interact Engagement Symposium (2017) and was featured on the BBC's Digital Planet 18th birthday show (2019)[83].

We have also formed collaborations with other university departments who are keen to include a Michelson interferometer as part of their own public engagement schemes. As a result of this work, our group has built a similar interactive interferometer for the University of East Anglia as well as additional smaller, more portable variations for our own use. Our website[28] details component lists and instructions for use by others to build their own interferometer. Alongside this, we are investigating making low-cost interferometer kits with novelty elements such as building blocks as a more affordable and fun means for schools to create their own Michelson interferometers similar to existing examples from the LIGO EPO group which use magnets [84] and glue [85].

VII. CONCLUSIONS AND FUTURE ACTIVITIES

At this exciting time in gravitational-wave research and discovery, our aim for this project was to bring this research to a wider community in an accessible way. We have designed and built a physical exhibit and custom-made exhibit software which are able to explain what gravitational waves are, how they are detected, and the recent discoveries. By installing the exhibit in the Thinktank Birmingham Science Museum, we have a long-term means of increasing the community awareness of the research taking place at a local university.

Looking further afield, the exhibit has also been shown at the 2017 RSSE. Attending a national science festival like this allows us to have a geographically wider reaching impact in the shorter term.

We have monitored the reception to our exhibit and taken action in response to what we have learnt. Upon re-installation to the Thinktank, the exhibit has upgraded custom software, greater user interaction, and is now in a more prominant museum position. We will continue to monitor and improve upon the installation via collaboration with the Thinktank staff and surveying the musuem visitors.

This project has led to further work in gravitational-wave public engagement, including collaborations with artists bringing this research to a potentially new audience at arts and music festivals. In the long term, the project will have a lasting role on an international scale with online instructions and parts lists[28] to enable others, including school groups, to build their own versions of this exhibit.

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